# Application of sediment core modelling to understanding climates of the past: An example from glacial-interglacial changes in Southern Ocean silica cycling

A. Ridgwell

Clim. Past Discuss., 2, 1371–1386, 2006
www.clim-past-discuss.net/2/1371/2006/


Climate of the Past Discussions

*Climate of the Past Discussions* is the access reviewed discussion forum of *Climate of the Past*



# Application of sediment core modelling to understanding climates of the past: An example from glacial-interglacial changes in Southern Ocean silica cycling

**A. Ridgwell**

School of Geographical Sciences, University of Bristol, Bristol, UK

Received: 4 December 2006 – Accepted: 9 December 2006 – Published: 20 December 2006

Correspondence to: A. Ridgwell (andy@seao2.org)

## Abstract

Paleoceanographic evidence from the Southern Ocean reveals an apparent stark meridional divide in biogeochemical dynamics associated with the glacial-interglacial cycles of the late Neogene. South of the present-day position of the Antarctic Polar Front biogenic opal is generally much more abundant in sediments during interglacials compared to glacials. To the north, an anti-phased relationship is observed, with maximum opal abundance instead occurring during glacials. This antagonistic response of sedimentary properties is an important model validation target for testing hypotheses of glacial-interglacial change, particularly with respect to understanding the causes of the variability in atmospheric $CO_2$. Here, I illustrate a time-dependent modelling approach to helping understand past climatic change by means of the generation of synthetic sediment core records. I find a close match between model-predicted and observed down-core changes in sedimentary opal content is achieved when changes in seasonal sea-ice extent is imposed, suggesting that the cryosphere is probably the primary driver of the striking features exhibited by the paleoceanographic record of this region.

## 1 Introduction

The Southern Ocean can be regarded as something of the Achilles Heel of the global carbon cycle, with changes in biological productivity (Martin, 1990; Watson et al., 2000), vertical mixing and stratification (Francois et al., 1997; Toggweiller, 1999; Toggweiller et al., 2006), and sea-ice cover (Stephens and Keeling, 2000) all potentially playing key roles in modifying atmospheric $CO_2$ on glacial-interglacial time scales. Changes in the surface ocean environment of this region will be manifested in interlinked properties of sedimentary material deposited to the ocean floor. However, the paleoceanographic evidence from the sediments of this region has not proved possible to interpret unambiguously (Anderson et al., 2002; Elderfield and Rickaby, 2000;

Sigman and Boyle, 2000). The difficulty in quantitative reconstruction of the surface environment directly from sedimentary properties is a consequence of different non-linear processes interacting to determine a particular sediment state (i.e., the measured proxy value). A promising model methodology has recently been developed to address this model-data divide – working forwards from an explicit description of the biogeochemical processes involved towards the data. By recording the properties of biogenic material preserved in deep-sea sediments within an ocean-sediment carbon cycle model, synthetic sediment cores can be generated (Heinze, 2001; Ridgwell, 2001[1]). This relatively data-friendly model output can then be contrasted rather directly with the sediment record. Here I illustrate the potential of this approach by evaluating the consequences of two possible drivers of glacial-interglacial environmental change in the Southern Ocean against observed changes in sedimentary opal content.

## 2 Modelling methodology

Here I use an ocean-sediment carbon cycle model based on an off-line representation of zonally-averaged ocean circulation (Stocker and Wright, 1996). To better resolve sea-ice cover, the two 7.5° zones south of 55° S in the parent model (Stocker and Wright, 1996) are sub-divided into a total of six sub-zones of width 2.5°. Each of these sub-zones is assumed to be characterized by the same vertical velocity as its parent zone with meridional velocities obtained by linear interpolation between 55° S and 62.5° S and extrapolation south of 62.5° S. Ocean-sediment biogeochemistry involves the cycling of three primary nutrients limiting to biological productivity (phosphate, silicic acid, and iron); similar to that of a previous glacial-interglacial study (Watson et al., 2000) but with explicit consideration of the dissolution of opal in the sediments (Ridgwell et al., 2003). A full description of the ocean carbon cycle model can be found in

[1] Ridgwell, A.: Sediment core modeling and the role of bioturbation: Lessons from lysocline shoaling at the PETM, Paleoceanography, submitted, 2006.

Ridgwell (2001).

The ocean is underlain by a series of discrete sediment modules handling ocean-sediment interactions Ridgwell (2001), similar in nature to earlier box modelling work (Munhoven and Francois, 1996; Walker and Opdyke, 1995). Each module comprises a single 5 cm thick (bioturbationally homogenized) surface layer in which dissolution of biogenic material proceeds. This layer lies atop a series of 1 cm thick sub-layers with a diffusive-like transfer imposed between them (representing the effect of deeper, less intense bioturbation). Excess solid material (i.e., rain minus dissolution flux) is exported out of this surface layer (buried) and stored in the uppermost sub-layer of the stack, thus building up a synthetic sediment record. Conversely, material is removed from the stack (eroded) should there be any deficit in the surface layer.

One advantage that synthetic sediments have over the data is that the precise (model) age of material deposited to the sediment surface is known. A numerical tracer of the time of deposition is used to tag calcite reaching the sediment surface, allowing a mean age for each sediment sub-layer to be tracked (Ridgwell, 2001[1]). In this way, an internal age-scale is generated, alleviating the need for the tuning of a $\delta^{18}O$ stratigraphy to an orbital template (Bassinot et al., 1994).

The model is run over approximately four glacial-interglacial cycles (400 kyr) following an initial 150 kyr spin-up. Ideally, the biogeochemical model would be informed by a suite of surface environmental boundary conditions (such as dust flux and sea-ice extent) generated internally within an integrated Earth system model. Instead, because this particular model lacks an interactive climate component, a time history of surface environmental boundary conditions is generated by the transformation of paired paleoclimatic reconstructions (made at discrete time slices) by a suitable continuous proxy signal.

## 3 Testing hypotheses for G-I change using synthetic sediment cores

Enhanced aeolian iron supply to the glacial Southern Ocean has been hypothesized to drive a stronger biological pump and lower the concentration of $CO_2$ in the atmosphere (Martin, 1990). Although considerable uncertainties remain regarding the operation of the iron cycle in this region (Ridgwell and Watson, 2002), results from ocean carbon cycle models go some way to supporting the iron hypothesis and suggest that changes in dust supply may have been responsible for anywhere between 5 and 45 ppm of the observed glacial-interglacial variability in atmospheric $CO_2$ (Archer et al., 2000; Bopp et al., 2003; Watson et al., 2000). The model predicted phasing between dust forcing and changes in $CO_2$ is also consistent with observations (Watson et al., 2000) despite arguments that an apparent lag in response of up to ~5 kyr exists (Broecker and Henderson, 1998).

In the underlying deep-sea sediments, records of biogenic opal content from the Atlantic and Indian sectors of the Southern Ocean reveal a pronounced meridional asymmetry (Anderson et al., 1998; Charles et al., 1991; Mortlock et al., 1991) (see Fig. 1), with glacial-interglacial changes in the composition of sediments lying approximately either side of the position of the present-day Antarctic Polar Front (APF) being opposite in sign. To the south, interglacial-age sediments are characterized by higher opal contents than that which occurs during glacial periods, while to the north, it is glacial sediments that are the more opal-rich. These changes are paralleled by indicators of Si utilization (De La Rocha et al., 1999), suggesting that the antagonistic sedimentary response in wt% opal primarily reflects a change in the surface ocean environment and biogenic opal export.

These two facets of the glacial-interglacial cycles are potentially intertwined as follows. The physiological effects of enhanced Fe availability on diatom cellular composition, particularly more efficient utilization of silicic acid (Watson et al., 2000) and consequently leakage (transport) to lower latitudes (Brzezinski et al., 2002; Matsumoto et al., 2002) could help explain the lower opal accumulation observed to the south of



CPD
2, 1371–1386, 2006
Modelling glacial-interglacial changes in sedimentary opal
A. Ridgwell

the APF (Sigman and Boyle, 2000). To test whether aeolian iron supply plays a fundamental controlling role in the export of biogenic material from the surface ocean, particularly of opal, the model is forced with a varying dust flux signal to the Southern Ocean (47.5–70.0° S), following Watson et al. (2000) (Fig. 1a).

The result of several hundred thousand years of sediment accumulation in the model is shown in Fig. 1(b,c). South of the APF, changes in aeolian iron supply has little effect on sedimentary opal content, while to the north, model sediments are strongly anti-phased with the data. Although glacial organic carbon export in the model is enhanced by ~100% south of the APF (driven by increased Fe availability), the model-parameterized effect of Fe availability on Si utilization efficiency by diatoms (Ridgwell, 2001) (manifested in the Si:C export ratio) restricts the increase in opal export to just ~35%, leaving little imprint on the sedimentary opal record. To the north, a slight reduction in advected Si supply coupled with greater Si utilization efficiency during glacial times combine to produce a substantial decrease in opal accumulation, contrary to the data. While different assumptions regarding the dependence of Si:C export ratios on Fe availability could conceivably improve the simulation, it is highly unlikely that a simultaneous match could be achieved to the data both north and south of the APF. Thus, although the effects of dust are consistent with the timing of the observed intra-glacial variability in atmospheric $CO_2$ (Ridgwell and Watson, 2002; Watson et al., 2000), the sedimentary (opal) record is not consistent with the iron hypothesis as a sole driver of biogeochemical changes in the Southern Ocean between glacials and interglacials.

Reconstructions of the cryosphere at the time of the Last Glacial Maximum (LGM) indicate that seasonal sea-ice cover was much more extensive than today in the Southern Ocean. In addition to being suggested as exerting a strong control on atmospheric $CO_2$ (Stephens and Keeling, 2000), this surface environmental change is also central to explanations for the observed paleoceanographic features of this region (Anderson et al., 2002; Charles et al., 1991; Crosta and Shemesh, 2002; Sigman and Boyle 2000). However, the highly non-linear nature of sedimentary opal preservation (Archer et al., 2000; Ridgwell et al., 2002) and the unobvious coupling relationship between opal export and sea-ice cover (Chase et al., 2003) point to the need for analysis within a numerical model to quantify whether changes in sea-ice extent could give rise to the features of the opal record. Seasonal sea-ice limits are now modified in the model with present-day wintertime and summertime fractional sea-ice coverage of each model grid point taken from CLIMAP (CLIMAP, 1976) and interpolated at intermediate months according to monthly insolation. The maximum and minimum seasonal limits are then varied over the course of approximately four glacial-interglacial cycles, taking information regarding the timing and rate of change from the Vostok temperature record (Petit et al., 1999) and taking the absolute amplitude of the envelope from the difference between present-day and LGM reconstructions (CLIMAP, 1976). This assumes that a first-order correspondence exists between sea-ice cover and Antarctic air temperature, an assumption supported by coupled climate model results (Gildor amd Ghil, 2002). The resulting forcing is shown in Fig. 2a.

In contrast to the large decrease in atmospheric $CO_2$ (>45 ppm) reported in a box model of the ocean carbon cycle (Stephens and Keeling, 2000) a relatively muted response (~7 ppm) is found here to increased glacial sea-ice cover in the Southern Ocean. This disparity may be a consequence of the lack of any explicit representation of equatorial up-welling zones (regions of intense $CO_2$ out-gassing in the modern ocean Takahashi et al., 1997) in more highly idealized box models which can result in the Southern Ocean becoming the dominant source of $CO_2$ to the (modern) atmosphere (Stephens and Keeling, 2000). While the sea-ice forcing has little apparent impact on the global carbon cycle it does drive a marked change in sediment composition (Fig. 2). The primary features of the opal record are now reproduced extremely well, particularly associated with transitions into and out of cold glacial stages (e.g., 2.2, 4.2, 6) and immediately following glacial inception. Crucially, the characteristic antagonistic variability either side of the APF is captured. This is a simple consequence of increased seasonal sea-ice cover south of the APF restricting biogenic export during glacials, with previously utilized nutrients advected northwards and fuelling greater (mainly diatom) export to the north (Anderson et al., 2002).

The information contained in the model sediments is determined by processes and environments representing large spatial means. In contrast, cores recovered from the deep sea may be influenced by local processes such as up-welling (Bertrand et al., 1996) and sediment redistribution by bottom currents (Bareille et al., 1994). Moreover, in order to maximize the temporal resolution of core data, drilling locations are often chosen where such local processes result in enhanced sedimentation rates. Close model-data correspondence in the absolute values of opal content is thus not expected a priori. Despite this, the match for core RC13-259 (Fig. 2b) is surprisingly good, lending confidence to the plausibility of the model assumptions. It should be noted that the sedimentary response to G-I perturbation has *not* been "tuned" in any way – adjustment of unconstrained parameter values is undertaken only in order to achieve a reasonable present-day ocean-sediment steady state (Ridgwell, 2001). Nor is there anything unique about the particular opal records chosen – alternative choices of pairs of observed and synthetic cores are found to exhibit similar matches. For instance, the model captures the prominent ~10–20 wt% opal highs associated with Isotope Stages 2.2, 4.2, and 6 in cores lying 5–10° further to the north (Mortlock et al., 1991). Interestingly, where the three sub Antarctic sectors are resolved, the model predicts significant inter-sector differences, with the amplitude of opal variability in the Pacific sector only about ~30–40% of that occurring at the same latitude in the Atlantic. This is consistent with opal and lithogenic flux data (Chase et al., 2003) and could reflect enhanced opal preservation in the Atlantic sector being facilitated by the greater flux of detrital material to the sediments there (Ridgwell et al., 2002).

Isotopic tracers can also be incorporated alongside bulk sediment fractions in the synthetic cores (Ridgwell, 2001[1]). For instance, simulations made of down-core variability in planktonic foraminiferal $\delta^{13}$C (not shown) suggest that sea-ice can also explain virtually all of the ~1 ‰ increase associated with the last deglacial transition exhibited by RC13-259 (Mortlock et al., 1991), consistent with interpretations of diatom-bound organic matter $\delta^{13}$C (Crosta and Shemesh, 2002).

Other reconstructions of the past state of the cryosphere have suggested that the minimum (summer-time) limit may have been little changed (Crosta et al., 1998) contrary to CLIMAP (CLIMAP, 1976). Driving the model with a seasonal sea-ice forcing making this alternative (summer-time) assumption results in little variability in opal content (<5 wt%) occurring either side of the APF. That the CLIMAP reconstruction enables the better fit to the opal data does not support any drastic revision of CLIMAP being required, as concluded by Gersonde and Zielinski (2000) on the basis of analyses of diatom sea-ice proxies. However, the simplicity of the coarse resolution zonally-averaged model used here severely limits its ability to make any detailed assessment of likely LGM sea-ice extents. In addition, no account is taken of changes in biogeochemical cycling due to the replacement of open ocean with seasonal ice zone ecosystems (Abelmann et al., 2006). The robust result that can be taken from this modelling example though is that the opal record must be closely linked (by a non-linear biogeochemical transformation) to the Antarctic climate signal (temperature), mostly likely mediated by changes in the seasonal limits of sea-ice extent.

The results presented here demonstrate that comparisons made between synthetic sediment cores and paleoceanographic data can provide important additional insights into the processes involved in glacial-interglacial change. Although in isolation, reduced aeolian iron supply can explain a significant (5 to 45 ppm) fraction of the initial observed deglacial increase in $CO_2$ (Archer et al., 2000; Bopp et al., 2003; Ridgwell, 2001; Watson et al., 2000), the synthetic sediment records highlight the existence of important omissions from this simplistic picture. Changes in the seasonal limits of sea-ice can account for much of the missing sedimentary control. Combined, the two surface ocean forcings give a slightly better simile of the opal data particularly south of the APF (not shown) than sea-ice alone. This beneficial interaction is not obvious from the effects of the two mechanisms in isolation, demonstrating the additional value of a mechanistic modelling approach. Simulation of additional proxies such as $\delta^{15}$N would allow the biogeochemical effects of further mechanisms such as ocean stratification (Crosta and Shemesh, 2002; Francois et al., 1997; Sigman and Boyle, 2000) to be disentangled from the sedimentary record.

## 4 Conclusions

A full understanding of the mechanisms responsible for glacial-interglacial changes in the global carbon cycle as exemplified by ice-core records of atmosphere composition still elude us. Given the substantial uncertainties in some of the key components of the global carbon cycle and the wide variety of different hypotheses proposed to account for the glacial control of $CO_2$, improved use of data constraints is vital for constraining and informing modelling work. By generating a model output that is comparable to the nature of the observed data, synthetic sediment cores provide a potentially powerful means of quantifying past climatic changes and compliment more traditional ways of interpreting the paleoceanographic record.

*Acknowledgements.* A. Ridgwell acknowledges the Royal Society for support under a University Research Fellowship.

## References

Abelmann A., Gersonde, R., Cortese, G., Kuhn, G., and Smetacek, V.: Extensive phytoplankton blooms in the Atlantic sector of the glacial Southern Ocean, Paleoceanography,21, 1013, doi:10.1029/2005PA001199, 2006.

Anderson, R. F., Kumar, N. R., Mortlock, A., Froelich, P. N., and Kubik, P.: Late-Quaternary changes in productivity of the Southern Ocean, J. Marine Syst., 17, 497–514, 1998.

Anderson, R. F., Chase, Z., Fleisher, M. Q., and Sachs, J.: The Southern Ocean's biologial pump during the Last Glacial Maximum, Deep-Sea Research II, 49, 1909–1938, 2002.

Archer, D., Winguth, A. Lea, D. & Mahowald, N.: What caused the glacial/interglacial atmospheric $p\mathrm{CO}_2$ cycles?, Reviews of Geophysics, 38, 159–189, 2000.

Bareille, G., Grousset, F. E., Labracherie, M., Labeyrie, L. D., and Petit, J. R.: Origin of detrital fluxes in the southeast Indian Ocean during the last climatic cycle, Paleoceanography, 9, 799–819, 1994.

Bassinot, F. C., Labeyrie, L. D., Vincent, E., Quidelleur, X., Shackleton, N. J., and Lancelot, Y.: The astronomical theory of climate and the age of the Brunhes-Matuyama magnetic reversal, Earth Planet Sc. Lett., 126, 91–108, 1994.

Bertrand, P., Shimmield, G., Martinez, P., Grousset, F., Jorissen, F., et al.: The glacial ocean productivity hypothesis – The important of regional temporal and spatial studies, Mar. Geol., 130, 1–9, 1996.

Bopp, L., Kohfeld, K. E., Le Quere, C., and Aumont, O.: Dust impact on marine biota and atmospheric $CO_2$ during glacial periods, Paleoceanography, 18, 1046, doi: 10.1029/2002PA000810, 2003.

Brzezinski, M. A., Pride, C. J., Franck, V. M., Sigman, D. M., and Sarmiento, J. L.: A switch from $Si(OH)_4$ to $NO_3^-$ depletion in the glacial Southern Ocean, Geophys. Res. Lett., 29, 1564, doi:10.1029/2001GL014349, 2002.

Broecker, W. S. and Henderson, G. M.: The sequence of events surrounding Termination II and their implications for the cause of glacial-interglacial $CO_2$ changes, Paleoceanography, 13, 352–364, 1998.

Charles, C. D., Froelich, P. N., Zibello, M. A., Mortlock, R. A., and Morley, J. J.: Biogenic opal in Southern Ocean sediments over the last 450 000 years: Implications for surface water chemistry and circulation, Paleoceanography, 6, 697–728, 1991.

Chase, Z., Anderson, R. F., Fleisher, M. Q., and Kubik, P. W.: Accumulation of biogenic and lithogenic material in the Pacific sector of the Southern Ocean during the past 40 000 years, Deep-Sea Research II 50, 799–832, 2003.

CLIMAP project members, The surface of the ice-age Earth, Science, 191, 1131–1137, 1976.

Crosta, X., Pichon, J. J., and Burckle, L. H.: Reappraisal of Antarctic seasonal sea-ice at the Last Glacial Maximum, Geophys. Res. Lett., 25, 2703–2706, 1998.

Crosta, X. and Shemesh, A.: Reconciling down core anticorrelation of diatom carbon and nitrogen isotopic ratios from the Southern Ocean, Paleoceanography, 17, 1010, 10.1029/2000PA000565, 2002.

De La Rocha, C. L., Brzezinski, M. A., DeNiro, M. J., and Shemesh, A.: Silicon-isotope composition of diatoms as an indicator of past oceanic change, Nature, 395, 680–683, 1999.

Elderfield, H. and Rickaby, R. E. M.: Oceanic Cd/P ratio and nutrient utilization in the glacial Southern Ocean, Nature, 405, 305–310, 2000.

Francois, R., Altabet, M. A., Yu, E.-F., Sigman, D. M., and Bacon, M. P.: Contribution of Southern Ocean surface-water stratification to low atmospheric $CO_2$ concentrations during the last glacial period, Nature, 389, 929–935, 1997.

Gersonde, R. and Zielinski, U.: The reconstruction of late Quaternary Antarctic sea-ice distribution – the use of diatoms as a proxy for sea-ice, Paloeography, Palaeoclimatology, Palaeoe-

cology, 162, 263–286, 2000.
Gildor, H. and Ghil, M.: Phase relations between climate proxy records: Potential effect of seasonal precipitation changes, Geophys. Res. Lett., 29, doi:10.1029/2001GL013781, 2002.
Heinze, C.: Towards the time dependent modeling of sediment core data on a global basis, Geophys. Res. Lett., 28, 4211–4214, 2001.
Köhler P. and Fischer, H.: Simulating low frequency changes in atmospheric $CO_2$ during the last 740 000 years, Clim. Past 2, 57–78, 2006.
Martin, J. H.: Glacial-interglacial $CO_2$ change; the iron hypothesis, Paleoceanography, 5, 1–13, 1990.
Matsumoto, K., Sarmiento, J. L., and Brzezinski, M. A.: Silicic acid leakage from the Southern Ocean: A possible explanation for glacial atmospheric $p$CO$_2$, Global Biogeochem. Cycles, 16, 1031, doi:10.1029/2001GB001442, 2002.
Mortlock, R. A., Charles, C. D., Froelich, P. N., Zibello, M. A., and Saltzman, J.: Evidence for lower productivity in the Antarctic Ocean during the last glaciation, Nature, 351, 220–222, 1991.
Munhoven, G. and Francois, L. M.: Glacial-interglacial variability of atmospheric $CO_2$ due to changing continental silicate rock weathering: A model study, J. Geophys. Res., 101, 21 423–21 437, 1996.
Petit, J. R., Jouzel, J., Raynaud, D., Barkov, N. I., and Barnola, J.-M.: Climate and Atmospheric History of the Past 420 000 years from the Vostok Ice Core, Antarctica, Nature, 399, 429–436, 1999.
Ridgwell, A. J.: Glacial-interglacial perturbations in the global carbon cycle, PhD thesis, Univ. of East Anglia at Norwich, (http://www.seao2.org/pubs/ridgwell_2001.pdf), UK, 2001.
Ridgwell, A. J. and Watson, A. J.: Feedback between aeolian dust, climate and atmospheric $CO_2$ in glacial time, Paleoceanography 17, 1059, doi:10.1029/2001PA000729, 2002.
Ridgwell, A. J., Watson, A. J., and Archer, D. A.: Modelling the response of the oceanic Si inventory to perturbation, and consequences for atmospheric $CO_2$, Global Biogeochem. Cycles, 16, 1071, doi:10.1029/2002GB001877, 2002.
Sigman, D. M. and Boyle, E. A.: Glacial/interglacial variations in atmospheric carbon dioxide, Nature, 407, 859–869, 2000.
Stephens, B. B. and Keeling, R. F.: The influence of Antarctic sea ice on glacial-interglacial $CO_2$ variations, Nature, 404, 171–174, 2000.
Stocker, T. F. and Wright, D. G.: Rapid changes in ocean circulation and atmospheric radiocar-

bon, Paleoceanography, 11, 773–795, 1996.
Takahashi, T., Feely, R. A., Weiss, R. F., Wanninkhof, R. H., and Chipman, D. W.: Global air-sea flux of $CO_2$: An estimate based on measurements of sea-air $pCO_2$ difference, Proc. Nat. Acad. Sci. U.S.A,. 94, 8292–8299, 1997.
Toggweiler, J. R.: Variation of atmospheric $CO_2$ by ventilation of the ocean's deepest water, Paleoceanography, 14, 571–588, 1999.
Toggweiler, J. R., Russell, J. L., and Carson, S. R.: Midlatitude westerlies, atmospheric $CO_2$ and climate change during the ice ages, Paleoceanography, 21, 2005, doi:10.1029/2005PA001154, 2006.
Walker, J. C. G. and Opdyke, B. C.: Influence of variable rates of netiric carbonate deposition on atmospheric carbon dioxide and pelagic sediments, Paleoceanography, 10, 415–427, 1995.
Watson, A. J., Bakker, D. C. E., Ridgwell, A. J., Boyd, P. W., and Law, C. S.: Effect of iron supply on Southern Ocean $CO_2$ uptake and implications for glacial atmospheric $CO_2$, Nature, 407, 730–733, 2000.

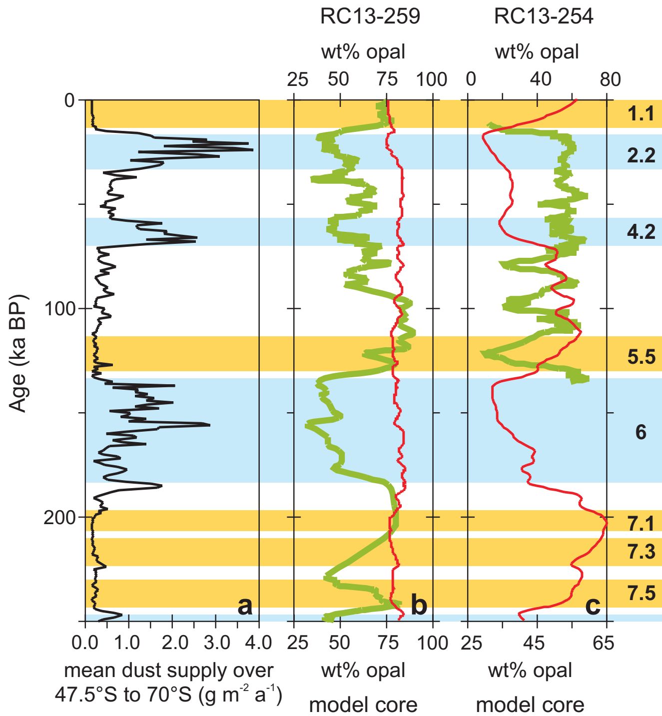


**Fig. 1.**



CPD

2, 1371–1386, 2006

**Fig. 1.** Influence of glacial-interglacial variability in aeolian Fe supply on the sedimentary opal record of the Southern Ocean. Warm (interglacial) and cold (peak glacial) marine isotope stages (Bassinot et al., 1994) are highlighted in orange and blue, respectively. **(a)**, Dust flux forcing (Watson et al., 2000) applied to the region 47.5° S to 70° S in the model. **(b–c)**, Observed (thick green line, top axis scale) and model-predicted (red line, bottom axis scale) down-core variability in wt% opal content for sediment cores lying either side of the APF. Observed data is based on a pair of cores (RC13-259; 53.9° S 04.9° W, RC13-254; 48.6° S 05.6° W) taken from the Atlantic Sector of the Southern Ocean (Charles et al., 1991; Mortlock et al., 1991). Core RC13-259 exhibits an anomalous pattern through Stages 3 and 4 compared to other cores south of the APF in this area (Mortlock et al., 1991) – the result of a hiatus occurring around this level (Anderson, R. F., personnel communication). Data from the nearby core RC11-77 (Burckle, L. H., personnel communication) is therefore spliced into the interval ~12–90 ka BP. Each synthetic core is recovered (Ridgwell, 2001[1]; Heinze, 2001) from a grid point having approximately the same frontal coordinate (Chase et al., 2003) (latitude relative to the position of the APF – taken to be at 55° S in the model) as the real cores (relative to the observed APF in the Atlantic sector of the Southern Ocean at ~50° S Mortlock et al., 1991). Synthetic sediment data is plotted using an internal age stratigraphy (Ridgwell, 2001[1]).

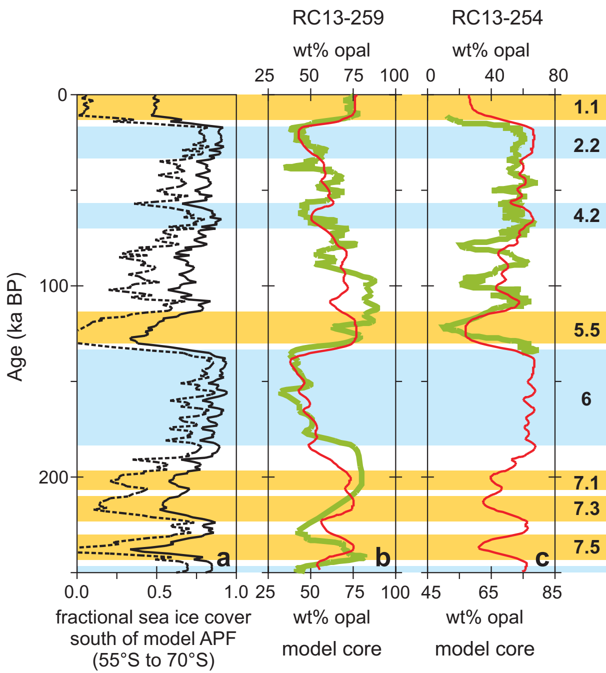


**Fig. 2.** The influence of glacial-interglacial variability in the seasonal limits of sea-ice extent on sedimentary opal content. **(a)**, Change in maximum/wintertime (continuous line) and minimum/summertime (dotted line) fractional sea-ice cover applied to the model Southern Ocean (shown averaged over all model grid points lying south of the APF). **(b–c)**, Observed (thick green line) and model-predicted (red line) down-core variability in opal content.